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# Impact of residual kidney function on hemodialysis adequacy and patient survival

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## ABSTRACT

**Background.** Both dialysis dose and residual kidney function (RKF) contribute to solute clearance and are associated with outcomes in hemodialysis patients. We hypothesized that the association between dialysis dose and mortality is attenuated with greater RKF.

**Methods.** Among 32 251 incident hemodialysis patients in a large US dialysis organization (2007–11), we examined the interaction between single-pool  $Kt/V$  (sp $Kt/V$ ) and renal urea clearance (rCL<sub>urea</sub>) levels in survival analyses using multivariable Cox proportional hazards regression model.

**Results.** The median rCL<sub>urea</sub> and mean baseline sp $Kt/V$  were 3.06 [interquartile range (IQR) 1.74–4.85] mL/min/1.73 m<sup>2</sup> and 1.32 ± 0.28, respectively. A total of 7444 (23%) patients died during the median follow-up of 1.2 years (IQR 0.5–2.2 years) with an incidence of 15.4 deaths per 100 patient-years. The Cox model with adjustment for case-mix and laboratory variables showed that rCL<sub>urea</sub> modified the association between sp $Kt/V$  and mortality ( $P_{\text{interaction}} = 0.03$ ); lower sp $Kt/V$  was associated with higher mortality among patients with low rCL<sub>urea</sub> (i.e. <3 mL/min/1.73 m<sup>2</sup>) but not among those with higher rCL<sub>urea</sub>. The adjusted mortality hazard ratios (aHRs) and 95% confidence intervals of the low (<1.2) versus high (≥1.2) sp $Kt/V$  were 1.40 (1.12–1.74), 1.21 (1.10–1.33), 1.06 (0.98–1.14), and 1.00 (0.93–1.08) for patients with rCL<sub>urea</sub> of 0.0, 1.0, 3.0 and 6.0 mL/min/1.73 m<sup>2</sup>, respectively.

**Conclusions.** Incident hemodialysis patients with substantial RKF do not exhibit the expected better survival at higher hemodialysis doses. RKF levels should be taken into account when deciding on the dose of dialysis treatment among incident hemodialysis patients.

**Keywords:** dialysis adequacy, dialysis dose, hemodialysis, residual kidney function, single-pool  $Kt/V$

## ADDITIONAL CONTENT

An author video to accompany this article is available at: [https://academic.oup.com/ndt/pages/author\\_videos](https://academic.oup.com/ndt/pages/author_videos).

## INTRODUCTION

Single-pool  $Kt/V_{\text{urea}}$  (sp $Kt/V$ , the clearance of urea multiplied by dialysis duration and normalized for urea distribution volume) or the urea reduction ratio (URR) is widely used for evaluating dialysis adequacy among patients with end-stage renal disease (ESRD) receiving maintenance hemodialysis. Dialysis dose as expressed in  $Kt/V_{\text{urea}}$  or URR has been suggested as an important predictor of morbidity and mortality in hemodialysis patients [1–6]. Currently sp $Kt/V$  is the most frequently applied measure of delivered dialysis dose, where the recommended minimum level is set to 1.2 of sp $Kt/V$  (equivalent to a URR of 65%) for thrice-weekly hemodialysis patients with little or no residual kidney function (RKF), according to the National Kidney Foundation–Kidney Disease Outcomes Quality Initiative (NKF-KDOQI) clinical practice guidelines [7].

RKF in ESRD patients may alter the dialysis dose–survival association, and the NKF-KDOQI guidelines in fact suggest that dialysis dose may be reduced for patients with substantial RKF provided that renal urea clearance is periodically measured [7]. Although many studies of peritoneal dialysis patients have shown that the association with better survival is found for greater RKF but not for higher delivered  $Kt/V$  [8–10], evidence for the optimal dialysis dose, either expressed in sp $Kt/V$  or URR, is still scarce among hemodialysis patients with RKF. This issue is increasing

its importance given that approximately 40% of ESRD patients have an estimated glomerular filtration rate  $\geq 10$  mL/min/1.73 m<sup>2</sup> at dialysis initiation [11] and given that the rates of RKF decline in hemodialysis patients may be similar to peritoneal dialysis patients under the current standard treatment with biocompatible membranes and bicarbonate buffer [12–14].

Although  $\text{spKt/V}$  remains a useful and common metric of dialysis adequacy [15] as employed in the ESRD Quality Incentive Program in the USA, the 2015 update in the KDOQI guidelines for hemodialysis adequacy did not make specific recommendations or suggestions on how to reduce the hemodialysis dose according to RKF levels because of lack of evidence [7]. Therefore we investigated the influence of RKF on the association between dialysis dose and mortality in a cohort of incident hemodialysis patients from a large dialysis organization in the USA. We hypothesized that in patients starting hemodialysis therapy with significant RKF, there is little to no association between dialysis dose and survival and that these patients would require lower initial dialysis doses than anuric patients.

## MATERIALS AND METHODS

### Patients

We retrospectively extracted, refined and examined data from all incident hemodialysis patients who initiated treatment between 2007 and 2011 in facilities operated by a large dialysis organization in the USA. Patients were considered to be on maintenance hemodialysis if they were treated for at least 60 consecutive days and were followed through 31 December 2011. Among 142 419 incident ESRD patients who were treated only by in-center thrice-weekly hemodialysis during the follow-up, we excluded 33 849 patients who died in the first 90 days of dialysis, 9958 who had missing data on baseline (i.e. the first quarter or 91 days of dialysis) variables of body mass index (BMI), hemoglobin, albumin, creatinine, calcium, phosphorus, parathyroid hormone (PTH), iron saturation, ferritin and carbon dioxide, 2470 who had missing data on baseline  $\text{spKt/V}$ , and 63 891 who had missing baseline data on URR or residual renal urea clearance ( $\text{rCL}_{\text{urea}}$ ) (Supplementary data, Figure S1). Our final study population consisted of 32 251 incident hemodialysis patients. The parent study was approved by the University of California Irvine Medical Center and University of Washington. Given the large sample size, anonymity of the patients studied and noninvasive nature of the research, the requirement for written consent was waived.

### Demographic, clinical and laboratory measures

Information on all-cause death, race/ethnicity, primary insurance, vascular access type, comorbidities and laboratory variables were obtained from the electronic database of the dialysis provider. To minimize measurement variability, averaged values of laboratory variables during the first patient-quarter (or the first 91 days of dialysis) within each patient served as baseline data and were used in all models.

Blood samples were drawn using uniform techniques in all dialysis clinics and were transported to the central laboratory in Deland, Florida, USA, typically within 24 h. All laboratory

values were measured by automated and standardized methods. Most blood laboratory values were measured monthly, including serum urea nitrogen, creatinine, albumin, calcium, phosphorus and bicarbonate. Serum ferritin and intact PTH were measured at least quarterly. Hemoglobin was measured at least monthly in all patients and weekly to biweekly in most patients. Most blood samples were collected predialysis with the exception of the postdialysis urea, which was obtained to calculate urea kinetics.

Residual  $\text{rCL}_{\text{urea}}$  was used as the index of RKF in all analyses. The average serum urea concentrations during urine collection were assumed to be 90% of the predialysis concentrations according to the Daugirdas approach [16] and thus  $\text{rCL}_{\text{urea}}$  was calculated as follows:

$$\text{rCL}_{\text{urea}} \text{ (mL/min)} = \frac{\text{urinary urea nitrogen (mg/dL)} \times \text{urinary volume (mL)}}{\text{collected time (min)} \times [0.9 \times \text{serum urea nitrogen (mg/dL)}]}$$

where serum urea nitrogen was obtained on the closest day within  $\pm 28$  days of urine collection. Urine collected time was reported as 1440 min in 98% of measurements, ranging from 720 to 2880 min.  $\text{rCL}_{\text{urea}}$  was then adjusted for body surface area and expressed as mL/min/1.73 m<sup>2</sup> [17, 18]. Normalized protein catabolic rate (nPCR) was calculated with accounting for  $\text{rCL}_{\text{urea}}$  [19].

$\text{SpKt/V}$  or URR was used as the index of hemodialysis adequacy. We used the second-generation logarithmic estimates of  $\text{spKt/V}$  [20, 21]:

$$\text{SpKt/V} = -\ln \left( R - \frac{0.0174}{\text{PIDI}} \times \frac{t}{60} \right) + \frac{(4 - 3.5 \times R) \times 0.55 \times \text{UF}}{V},$$

where  $R$  is the ratio of the pre- and posthemodialysis concentrations of serum urea,  $\text{PIDI}$  is the length of the preceding interdialysis interval (days),  $t$  is the duration of hemodialysis treatment time (minutes),  $\text{UF}$  is the amount of ultrafiltration (L) during the given hemodialysis session and  $V$  is the estimated urea distribution volume.

### Statistical analyses

Patients were categorized into two groups according to baseline  $\text{rCL}_{\text{urea}}$  strata ( $< 3.0$  or  $\geq 3.0$  mL/min/1.73 m<sup>2</sup>). The cutoff value of 3.0 mL/min/1.73 m<sup>2</sup> was selected based on the definition of ‘substantial RKF’ in previous studies and guidelines [22, 23]. Differences in baseline characteristics between included versus excluded patients and between two  $\text{rCL}_{\text{urea}}$  strata were compared by standardized differences due to the large sample size of this study [24, 25]. Since the missing frequency was high in  $\text{rCL}_{\text{urea}}$ , we used inverse probability weighting to mitigate selection bias in our observational study [26]. In short, the probability of having data on  $\text{rCL}_{\text{urea}}$  were calculated among patients with data on all covariates except for  $\text{rCL}_{\text{urea}}$  and nPCR that accounted for  $\text{rCL}_{\text{urea}}$  by a logistic regression model and patients were weighted based on their inverse probabilities.  $\text{SpKt/V}$  and URR were treated as categorical variables in the primary analyses and their association with all-cause mortality was examined by inverse probability-weighted Cox proportional hazards models.

As the sensitivity analyses, we also examined potential nonlinear relationships by using restricted cubic spline functions with four knots at the 5th, 35th, 65th and 95th percentiles of each index and the reference  $\text{spKt/V}$  and URR were 1.4 and 0.65, respectively.

For each analysis we employed hierarchical adjustment with four models as follows:

1. Model 1 included baseline  $\text{spKt/V}$  or URR.
2. Model 2 included the above variables plus case-mix variables including age, sex, race/ethnicity, primary insurance, central venous catheter use, hypertension, diabetes, history of cardiovascular disease (i.e. congestive heart failure, atherosclerotic heart disease, cerebrovascular disease or other cardiovascular disease) and  $\text{rCL}_{\text{urea}}$ .
3. Model 3 included the above variables plus BMI, nPCR, hemoglobin, serum albumin, creatinine, calcium, iron saturation, total bicarbonate and ferritin.
4. Model 4 included the above variables plus serum phosphorus and natural log-transformed intact PTH.

We defined Model 3 as the primary model because serum phosphorus and intact PTH may be located in the pathways between  $\text{spKt/V}$  and mortality (i.e. intermediates) [27–30]. We also did not include volume parameters such as interdialytic weight gain and ultrafiltration rate in the adjustment models since these factors are considered intermediates. Effect modification of the association between  $\text{spKt/V}$  or URR and mortality were evaluated by adding a product term between continuous  $\text{spKt/V}$  and each of *a priori*-defined variables, including baseline age ( $\geq 65$  or  $< 65$  years), gender, race (white or nonwhite), diabetes, presence of congestive heart failure, serum albumin ( $\geq 3.6$  or  $< 3.6$  g/dL) and BMI ( $\geq 30$  or  $< 30$ ) into Model 3 and by conducting the subgroup analyses in each  $\text{rCL}_{\text{urea}}$  category. Additionally we evaluated the change in the mortality risk associated with low  $\text{spKt/V}$  ( $< 1.2$  versus  $\geq 1.2$ ) over  $\text{rCL}_{\text{urea}}$  levels by including restricted cubic spline functions for  $\text{rCL}_{\text{urea}}$  and their interactions with low  $\text{spKt/V}$  in Model 3.

The frequency of missing data was 6% for nPCR, and multiple imputation methods with five data sets were used in all regression analyses. Analyses were conducted using STATA MP version 13.1 (StataCorp, College Station, TX, USA).

## RESULTS

### Baseline characteristics

The cohort included 32 251 incident hemodialysis patients in whom the mean  $\pm$  SD age was  $62 \pm 15$  years, of which 63% were male, 54% were Caucasian, 28% were African American and 59% were diabetic. Mean baseline  $\text{spKt/V}$  and URR were  $1.32 \pm 0.28$  and  $0.66 \pm 0.07$ , respectively. The median  $\text{rCL}_{\text{urea}}$  was 3.06 [interquartile range (IQR) 1.74–4.85] mL/min/1.73 m<sup>2</sup> and the prevalence of patients with low ( $< 3.0$  mL/min/1.73 m<sup>2</sup>) and high ( $\geq 3.0$  mL/min/1.73 m<sup>2</sup>)  $\text{rCL}_{\text{urea}}$  levels were 49 and 51%, respectively. Patients with greater  $\text{rCL}_{\text{urea}}$  tended to be male; had lower levels of  $\text{spKt/V}$ , URR, serum creatinine and phosphorus and had higher levels of nPCR and hemoglobin

(Table 1). A total of 7444 (23%) patients died during the median follow-up of 1.2 years (IQR 0.5–2.2) with an incidence of 15.4 deaths per 100 patient-years. Compared with 76 319 excluded patients, 32 251 included patients were more likely to be male, Caucasian and had lower  $\text{spKt/V}$  and URR levels (standardized difference  $> 0.2$ ; Supplementary data, Table S1). After weighting patients by inverse probability of having data on  $\text{rCL}_{\text{urea}}$  and nPCR, those variables were well balanced between those with versus without  $\text{rCL}_{\text{urea}}$  (Supplementary data, Table S2).

### Association of $\text{spKt/V}$ and all-cause mortality according to $\text{rCL}_{\text{urea}}$ strata

There was a trend toward higher mortality risk across higher  $\text{spKt/V}$  levels in the unadjusted model (i.e. Model 1) in high  $\text{rCL}_{\text{urea}}$  category ( $P_{\text{trend}} = 0.8$  and  $< 0.001$  for the low and high  $\text{rCL}_{\text{urea}}$ , respectively; Figure 1). However, the association between  $\text{spKt/V}$  and all-cause mortality was significantly modified by  $\text{rCL}_{\text{urea}}$  levels after adjustment for case-mix variables and laboratory variables ( $P_{\text{interaction}} = 0.01$  and  $0.03$  for Models 2 and 3, respectively). In Model 3 there was a significant trend toward higher mortality across lower  $\text{spKt/V}$  categories among patients with low  $\text{rCL}_{\text{urea}}$  ( $P_{\text{trend}} < 0.001$ ) but not among those with high  $\text{rCL}_{\text{urea}}$  ( $P_{\text{trend}} = 0.4$ ), and the adjusted hazard ratio (aHR) for mortality of the lowest ( $< 1.0$ ) versus the middle (1.2–1.4)  $\text{spKt/V}$  quintile group was 1.17 [95% confidence interval (CI) 1.00–1.38] and 1.08 (95% CI 0.95–1.23) for patients with low versus high  $\text{rCL}_{\text{urea}}$ , respectively.

We then evaluated the mortality risk associated with low  $\text{spKt/V}$  ( $< 1.2$  versus  $\geq 1.2$ ) over  $\text{rCL}_{\text{urea}}$  levels using spline functions for  $\text{rCL}_{\text{urea}}$  and their interactions with low  $\text{spKt/V}$  (Figure 2). The risk associated with low  $\text{spKt/V}$  was higher with lower  $\text{rCL}_{\text{urea}}$ , showing an increased mortality risk in the range of  $\text{rCL}_{\text{urea}} < 3.0$  mL/min/1.73 m<sup>2</sup> with aHRs of 1.21 (95% CI 1.10–1.33) and 1.11 (95% CI 1.04–1.20) at  $\text{rCL}_{\text{urea}}$  of 1.0 and 2.0 mL/min/1.73 m<sup>2</sup>, respectively. Meanwhile, low  $\text{spKt/V}$  was not associated with mortality in greater  $\text{rCL}_{\text{urea}}$  levels with aHRs of 1.06 (95% CI 0.98–1.14) and 1.00 (95% CI 0.93–1.08) at  $\text{rCL}_{\text{urea}}$  of 3.0 and 6.0 mL/min/1.73 m<sup>2</sup>, respectively. Consistent associations were observed in Models 2, 3 and 4 (Supplementary data, Figure S2).

In Model 4, which included serum phosphorus and natural intact PTH on top of the variables in Model 3, the modification of the association between  $\text{spKt/V}$  and mortality by  $\text{rCL}_{\text{urea}}$  was attenuated ( $P_{\text{interaction}} = 0.06$ ), which may be due to overadjustment because phosphorus and intact PTH may be at least partly intermediates between  $\text{spKt/V}$  and mortality.

### Subgroup analysis of the association between $\text{spKt/V}$ and all-cause mortality according to $\text{rCL}_{\text{urea}}$ strata

Subgroup analysis of the associations of low ( $< 1.2$ ) and high ( $\geq 1.4$ )  $\text{spKt/V}$  with mortality were examined in Model 3 (reference 1.2– $< 1.4$ ). Consistent with the findings above, a significant trend was observed between lower  $\text{spKt/V}$  categories and higher mortality among patients with low  $\text{rCL}_{\text{urea}}$  ( $P_{\text{trend}} < 0.001$ ) but not among those with high  $\text{rCL}_{\text{urea}}$  ( $P_{\text{trend}} = 0.4$ ; Figure 3). Among patients with low  $\text{rCL}_{\text{urea}}$ , the

**Table 1. Baseline characteristics of 32 251 incident hemodialysis patients stratified by baseline residual rCL<sub>urea</sub>**

Characteristics	Total ( <i>n</i> = 32 251)	rCL <sub>urea</sub> (mL/min/1.73 m <sup>2</sup> )		Standardized difference
		<3.0 ( <i>n</i> = 15 786)	≥3.0 ( <i>n</i> = 16 465)	
CL <sub>urea</sub> (mL/min/1.73 m <sup>2</sup> ), median (IQR)	3.06 (1.74–4.85)	1.72 (1.05–2.35)	4.80 (3.80–6.40)	2.03
Urine volume (mL/24 h), median (IQR)	800 (490–1300)	500 (300–700)	1200 (850–1675)	1.74
Age (years), mean ± SD	61.9 ± 14.8	62.3 ± 15.3	61.5 ± 14.3	−0.05
Male, %	63	57	69	0.25
Race, %				
White	54	51	58	0.14
Black	28	31	24	−0.16
Hispanic	11	11	11	−0.02
Asian and others	7	7	8	0.04
Primary insurance, %				
Medicare	51	53	50	−0.06
Medicaid	6	7	6	−0.04
Others	42	40	44	0.08
Vascular access, %				
Central venous catheter	74	77	70	−0.16
AV fistula/graft	22	18	26	0.18
Unknown	4	4	4	0.00
Comorbidities, %				
Diabetes	59	58	61	0.07
Hypertension	51	53	49	−0.08
Congestive heart failure	39	40	38	−0.04
Atherosclerotic heart disease	14	14	14	0.01
Cerebrovascular	2	2	1	−0.02
Other cardiovascular disease	15	16	15	−0.01
Dyslipidemia	26	26	27	0.03
Infection	81	82	81	−0.01
Malignancy	3	3	2	−0.01
spKt/V, mean ± SD	1.32 ± 0.28	1.37 ± 0.28	1.28 ± 0.27	−0.31
Urea reduction ratio (%), mean ± SD	66 ± 7	67 ± 7	65 ± 7	−0.29
Body mass index (kg/m <sup>2</sup> ), median (IQR)	27.4 (23.6–32.6)	27.3 (23.5–32.7)	27.5 (23.8–32.6)	0.03
Weekday IDWG (kg), median (IQR)	1.7 (1.2–2.4)	1.8 (1.2–2.4)	1.7 (1.1–2.4)	−0.11
Weekend IDWG (kg), median (IQR)	2.4 (1.6–3.3)	2.5 (1.7–3.4)	2.2 (1.5–3.1)	−0.20
Ultrafiltration rate (L/h), mean ± SD	0.59 ± 0.24	0.61 ± 0.23	0.57 ± 0.25	−0.13
nPCR (g/kg/day), mean ± SD	0.98 ± 0.28	0.90 ± 0.25	1.06 ± 0.29	0.58
ESRD reason, %				
Diabetes	47	45	49	0.10
Hypertension	28	31	26	−0.10
Glomerulonephritis	10	10	10	0.00
Cystic kidney disease	2	2	2	0.05
Other	13	13	12	−0.03
Laboratory variables				
Hemoglobin (g/dL), mean ± SD	11.3 ± 1.1	11.1 ± 1.1	11.4 ± 1.1	0.20
Albumin (g/dL), mean ± SD	3.57 ± 0.46	3.54 ± 0.46	3.60 ± 0.45	0.14
Creatinine (mg/dL), mean ± SD	5.9 ± 2.3	6.5 ± 2.6	5.3 ± 1.9	−0.55
Corrected calcium (mg/dL), mean ± SD	9.1 ± 0.5	9.1 ± 0.6	9.1 ± 0.5	0.00
Phosphorus (mg/dL), mean ± SD	5.0 ± 1.1	5.2 ± 1.2	4.8 ± 1.0	−0.28
Intact PTH (pg/mL), median (IQR)	315 (203–478)	332 (213–514)	300 (194–446)	−0.17
Iron saturation (%), mean ± SD	23 ± 8	23 ± 8	23 ± 8	−0.01
Ferritin (ng/mL), median (IQR)	268 (156–448)	281 (165–472)	255 (148–427)	−0.13
Bicarbonate (mEq/L), mean ± SD	23.4 ± 2.6	23.6 ± 2.6	23.2 ± 2.6	−0.15

Conversion factors for units: albumin and hemoglobin in g/dL to g/L, 10; creatinine in mg/dL to mmol/L, 88.4; calcium in mg/dL to mmol/L, 0.2495; phosphorus in mg/dL to mmol/L, 0.3229. No conversion is necessary for ferritin in ng/mL and mg/L. IDWG, interdialytic weight gain.

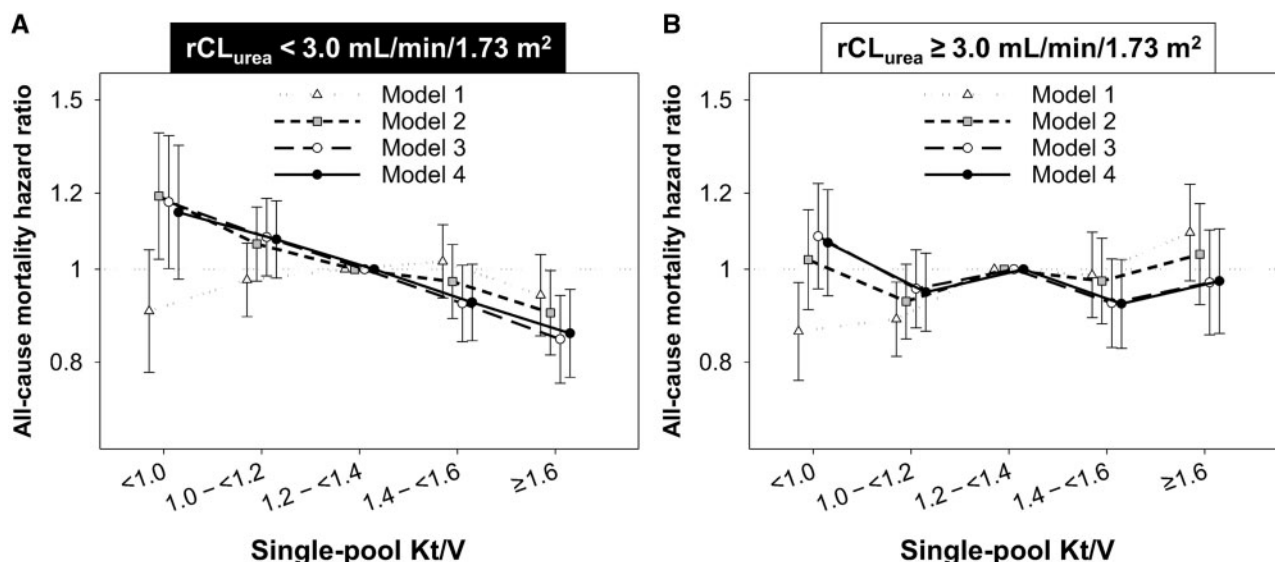
association between spKt/V and mortality was not modified by baseline age, gender, race, diabetes, presence of congestive heart failure, serum albumin and BMI ( $P_{\text{interaction}} > 0.05$  for all; Figure 3A). However, among patients with high rCL<sub>urea</sub> levels, the association between spKt/V and mortality was modified by gender ( $P_{\text{interaction}} = 0.01$ ) where low spKt/V was associated with higher mortality risk in female

( $P_{\text{trend}} = 0.01$ ) but not in male patients ( $P_{\text{trend}} = 0.4$ ; Figure 3B).

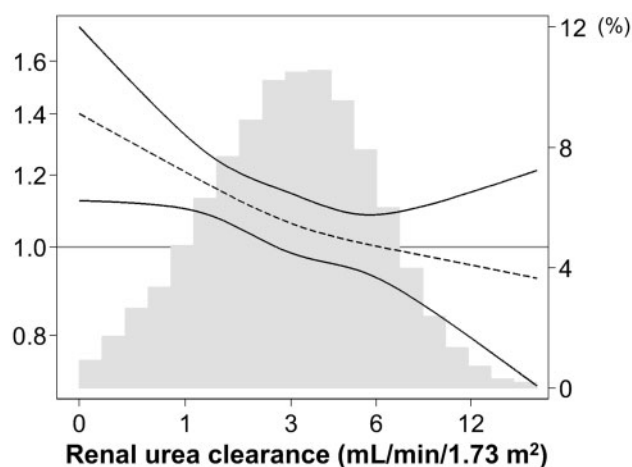
### Sensitivity analysis using URR

The associations of URR with mortality in Models 1–4 were consistent with those of spKt/V. The Model 3 aHRs of the lowest (<0.60) and highest (≥0.75) URR, when compared with the





**FIGURE 1:** Association of baseline spKt/V with all-cause mortality in 32 251 incident hemodialysis patients with baseline rCL<sub>urea</sub> of (A) <3.0 mL/min/1.73 m<sup>2</sup> and (B) ≥3.0 mL/min/1.73 m<sup>2</sup> in four adjusted models.



**FIGURE 2:** The change in the mortality risk associated with low spKt/V (<1.2 versus ≥1.2) over rCL<sub>urea</sub> levels in 32 251 incident hemodialysis patients.

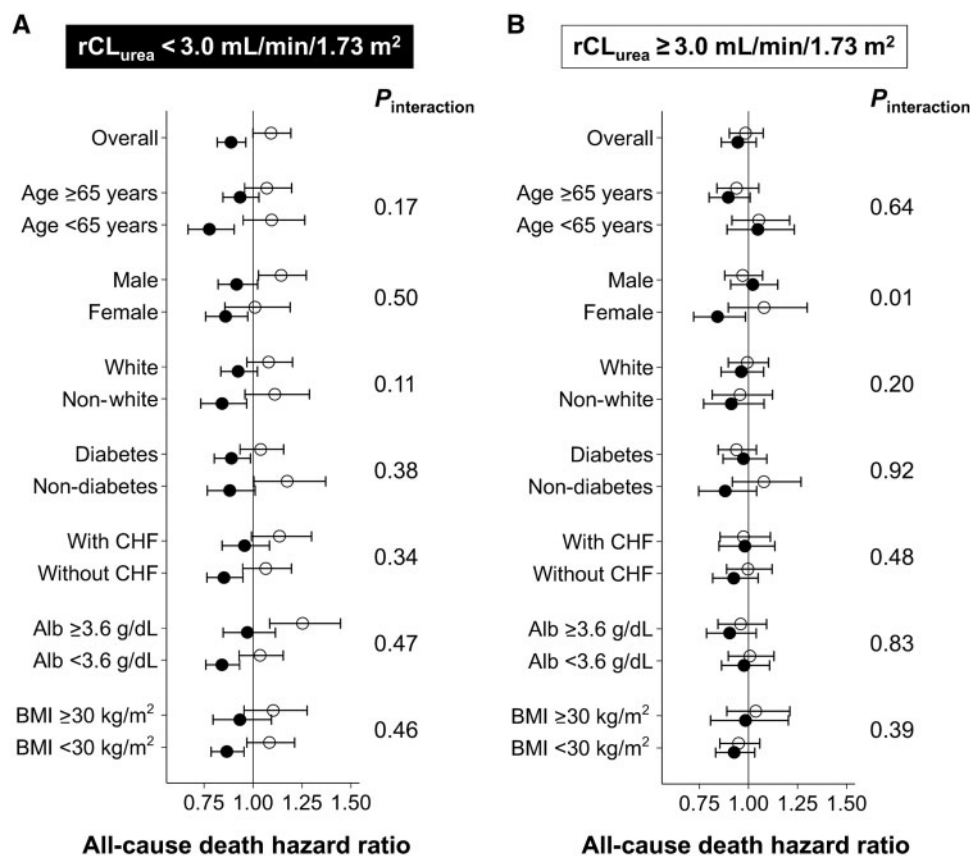
middle URR (0.65–0.70), were 1.20 (95% CI 1.07–1.35) and 0.86 (95% CI 0.77–0.97), respectively, for patients with low rCL<sub>urea</sub> ( $P_{\text{trend}} < 0.001$ ) and 1.09 (95% CI 0.98–1.22) and 0.95 (95% CI 0.82–1.09), respectively, for patients with high rCL<sub>urea</sub> ( $P_{\text{trend}} = 0.1$ ; Figure 4). Models using spline functions yielded consistent results (Supplementary data, Figure S3).

In subgroup analysis using three URR categories (<0.65, 0.65–<0.70 and ≥0.70), the mortality risk of low URR was further pronounced among patients with low rCL<sub>urea</sub> whereas the association between low URR and higher mortality was attenuated if serum albumin level was low ( $P_{\text{interaction}} = 0.03$ ) (Figure 5A). Similar to the results based on spKt/V, among patients with high rCL<sub>urea</sub>, there was a significant trend toward lower mortality across higher URR categories when patients were female ( $P_{\text{trend}} = 0.002$ ) but not when patients were male ( $P_{\text{trend}} = 0.5$ ,  $P_{\text{interaction}} = 0.01$ ; Figure 5B).

## DISCUSSION

In the present study, the association of a higher spKt/V (or URR) with better survival was observed among patients with low RKF (rCL<sub>urea</sub> <3.0 mL/min/1.73 m<sup>2</sup>) but was attenuated among those with substantial RKF (rCL<sub>urea</sub> ≥3.0 mL/min/1.73 m<sup>2</sup>). The 2006 updates on the KDOQI clinical practice guidelines underscored that the cutoff value of 1.2 for minimum spKt/V can be applied to patients with little or no RKF since it was derived from studies excluding patients with RKF or those assuming no RKF among participants [23, 31, 32]. Our results were consistent with these previous studies in terms of the dialysis dose–mortality association among patients with low rCL<sub>urea</sub> [28, 33–35]. The 2006 KDOQI guidelines also suggest that the minimum spKt/V can be reduced for patients with substantial RKF based on the urea kinetic model indicating that rCL<sub>urea</sub> of 2.0 mL/min/1.73 m<sup>2</sup> corresponds to ~0.67 weekly Kt/V [23], but there has been little evidence supporting this kinetic model–derived hypothesis. A recent study by Swaminathan *et al.* [36] indicated that ≥4 h of dialysis treatment (versus 3 h) is associated with a lower mortality risk among incident hemodialysis patients. Because dialysis dose increases with longer treatment time, these study results may seem to conflict with ours; however, our study differs by our evaluation of effect modification by RKF.

Our finding that the association of dialysis dose with mortality is strongly dependent on RKF levels is consistent with the Netherlands Cooperative Study on the Adequacy of Dialysis (NECOSAD)-2 study, where lower dialysis dose was incrementally associated with higher mortality only among anuric patients [37]. Both studies included incident hemodialysis patients, but these discrepant cutoff values in rCL<sub>urea</sub> (i.e. ≥3.0 versus <3.0 mL/min/1.73 m<sup>2</sup> in our study and the presence versus absence of RKF in the NECOSAD-2 study) may result from the difference in analytical methods; the NECOSAD-2 study used a time-varying covariate Cox model



**FIGURE 3:** Association of baseline URR with all-cause mortality in 32 251 incident hemodialysis patients with baseline  $rCL_{urea}$  of (A)  $< 3.0 \text{ mL/min/1.73 m}^2$  and (B)  $\geq 3.0 \text{ mL/min/1.73 m}^2$  in four adjusted models.

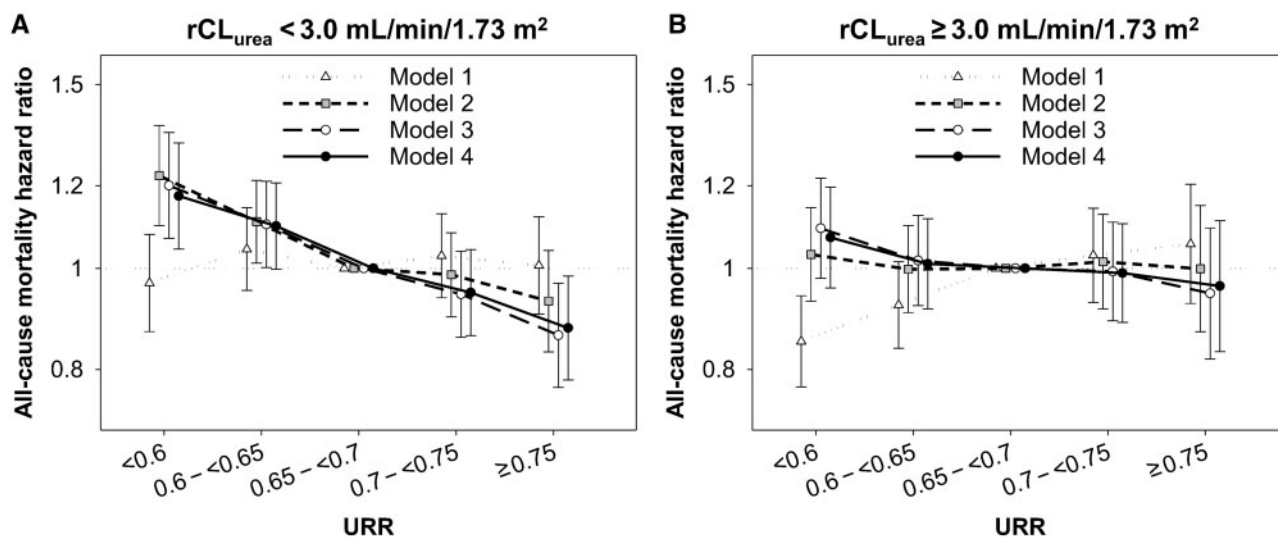
to evaluate short-term associations, while we focused on long-term associations by using a conventional fixed covariate Cox model considering the time frame required for dialysis dose to impact on patient survival.

Given that incident ESRD patients start dialysis at a wide range of RKF levels and that the benefit of greater RKF is substantial even at such small differences as observed in this population, simple dichotomization may not be adequate to untangle the interactions among RKF, dialysis adequacy and survival. The large sample size of this study enabled us to demonstrate that the risk associated with low  $spKt/V$  (i.e.  $< 1.2$  versus  $\geq 1.2$ ) was linearly attenuated with greater  $CL_{urea}$ . We also provided specific HRs of low  $spKt/V$  for all-cause mortality at different  $CL_{urea}$  levels. These detailed data allow us to assess the potential risk associated with low dialysis dose based on the individual RKF level of each patient, which may facilitate tailored dialysis prescriptions in future clinical practice.

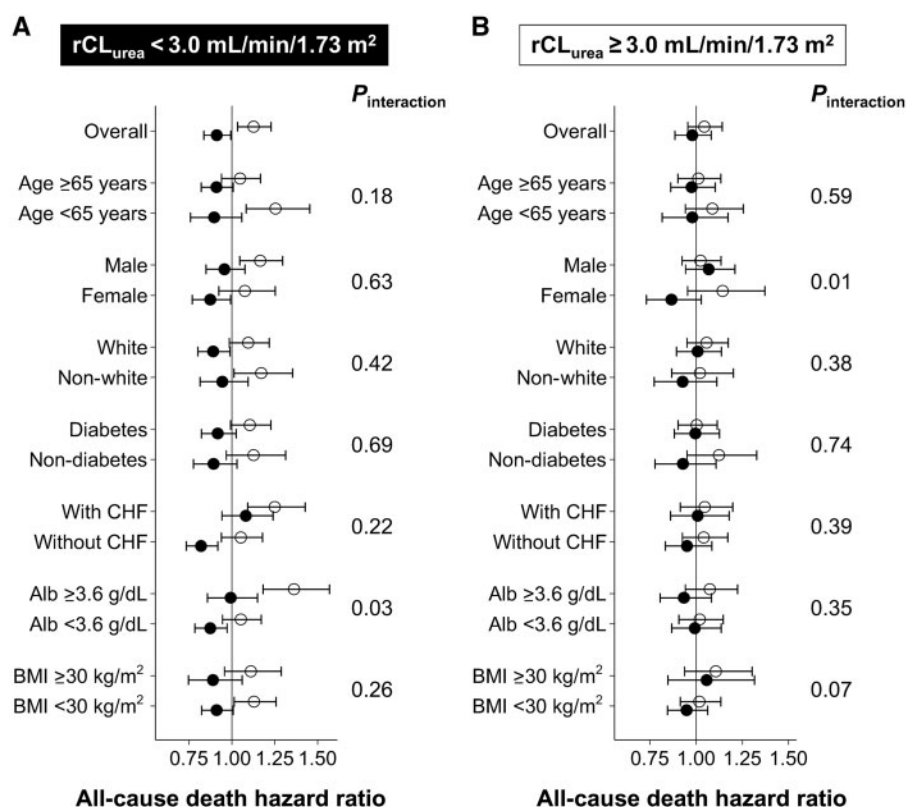
Our results are also supported by a recent observational study demonstrating that incident hemodialysis patients on incremental frequency regimens (i.e. starting hemodialysis with a twice-weekly schedule), which is inherently accompanied by reduced dialysis dose, experienced a similar mortality as those with conventional thrice-weekly regimens if patients had substantial RKF [38]. These two studies are complementary to each other, but the findings of this study can be applicable to a much wider population given that the vast majority of hemodialysis patients in developed countries routinely receive thrice-weekly treatment.

Patients with greater RKF experienced less weekend interdialytic weight gain in this study. Given that an excess of ultrafiltration or intradialytic hypotension in relation to interdialytic weight gain has been associated with higher mortality in both incident and prevalent hemodialysis patients [39–42], more stable intradialytic hemodynamics resulting from less ultrafiltration among patients with greater RKF may partly explain the attenuation in the association between dialysis adequacy and mortality. Additionally, such hemodynamic stability may also preserve more RKF, leading to a positive feedback loop. Other proposed strategies to preserve RKF include avoidance of nephrotoxic agents, a low-protein diet on nondialysis days, the use of ultrapure dialysate and an incremental/infrequent approach to hemodialysis initiation [43].

Higher dialysis dose was consistently associated with lower mortality among women, even if they had substantial RKF. As a urea distribution volume-based scaling of dialysis dose,  $spKt/V$  is often overestimated in women, especially in small-size women, due to their relatively less water-rich muscle mass and possibly due to RKF [44–46], whereby women may be underdialyzed under standard  $spKt/V$ . Indeed, the Hemodialysis (HEMO) Study suggested that the intensive dialysis dose, compared with the standard dose, reduced mortality and morbidity in women but not in men [27]. A consistent finding was observed among patients with substantial RKF in our study. However, it remains unclear why the interaction between gender and dialysis dose was not observed among patients with little or



**FIGURE 4:** Overall and subgroup analysis of association between  $spKt/V$  and all-cause mortality in 32 251 incident hemodialysis patients with baseline  $rCL_{urea}$  of (A)  $<3.0$  mL/min/1.73  $m^2$  and (B)  $\geq 3.0$  mL/min/1.73  $m^2$  in Model 3. Points and bars represent HR estimates and 95% CIs, respectively. Alb, albumin; BMI, body mass index; CHF, congestive heart failure; DM, diabetes mellitus.



**FIGURE 5:** Overall and subgroup analysis of association between URR and all-cause mortality in 32 251 incident hemodialysis patients with baseline  $rCL_{urea}$  of (A)  $<3.0$  mL/min/1.73  $m^2$  and (B)  $\geq 3.0$  mL/min/1.73  $m^2$  in Model 3. Points and bars represent HR estimates and 95% CIs, respectively. Alb, albumin; BMI, body mass index; CHF, congestive heart failure; DM, diabetes mellitus.

no RKF. These results should be considered suggestive due to multiple comparisons and need to be verified in future studies.

Among patients with low  $rCL_{urea}$ , the association between low URR and greater mortality was attenuated while the association between high URR and lower mortality was pronounced if the patient had low albumin levels. However, these

findings were not confirmed by using  $spKt/V$  as an index of dialysis dose. Nevertheless, trends of the change in the absolute effect size were similar between URR and  $spKt/V$  in either case. A higher threshold of dialysis dose may be necessary for patients with higher serum albumin if they have low or little RKF.



There have been conflicting data among large clinical trials evaluating dialysis dose and frequency. For example, while maintaining lower urea nitrogen concentrations decreased treatment withdrawals and hospitalizations in the National Cooperative Dialysis Study [31], higher dialysis dose did not improve patient survival in the HEMO Study [47]. Additionally, the Frequent Hemodialysis Network reported better survival with daily six-times-per-week in-center hemodialysis [48] and higher mortality with nocturnal six-times-per-week home hemodialysis [29] compared with conventional thrice-weekly in-center hemodialysis. Although the reasons for those inconsistent results remain unclear, it should be noted that clinical trials generally have limited external validity and inadequate statistical power to detect heterogeneity in the treatment effect. The efficacy of higher dialysis adequacy may actually be modified by several factors, including patient body size, dialysis vintage, treatment time, treatment frequency and RKF [7]. Our findings support the potential of RKF as a strong and linear effect modifier, which needs to be examined in further studies. Although, due to the observational nature of this study, we cannot prove causality between dialysis dose and mortality, the currently recommended minimum dialysis dose (i.e. 1.2 in  $\text{spKt/V}$ ) is also based on observational studies and is applicable only in patients with  $\text{rCL}_{\text{urea}} < 2.0 \text{ mL/min/1.73 m}^2$  [7].

Our study should be qualified for several other limitations. First, there may also be residual confounding or unmeasured confounders such as inadequate predialysis care. Second,  $\text{spKt/V}$  and URR may have varied over time. We focused on the long-term association of dialysis dose in the early period of dialysis with long-term mortality in this study, and further studies are required to examine the relationships among longitudinal changes in dialysis dose, RKF decline and mortality. Third, RKF may not be accurate given the use of urea clearance, the difficulties in punctual and complete collection of urine samples and the use of factor 0.9 for estimating average predialysis serum urea. Nevertheless, the population-level associations can be estimated from an adequate number of subjects if such errors are not associated with the outcome, and a recent study has shown that the change in  $\text{rCL}_{\text{urea}}$  used in this study was closely related to all-cause mortality [22]. Fourth, medications were not included in the adjustment model. However, in contrast to the peritoneal dialysis population, even renin-angiotensin system inhibitors, the representative renoprotective drug type, do not have any effect on RKF among hemodialysis patients [49]. In addition, potential selection bias may exist since patients with limited RKF are less likely to have undergone urine collections. The employment of inverse probability weighting for having data on RKF is our best effort to mitigate selection bias in this study. Nevertheless, our findings may not be extrapolated to those settings with different practice patterns from the USA, such as dialyzer reuse, inadequate water purification and schedules other than thrice-weekly treatment.

In conclusion, RKF at dialysis start modified the association of initial dialysis dose with all-cause mortality among incident hemodialysis patients. Further research, including clinical trials, is necessary to test if an incremental hemodialysis approach with a reduced dialysis dose by either less treatment time or a less frequent schedule among patients with substantial RKF

during the first several months of dialysis is an economic strategy that enhances patients' quality of life without compromising their survival [50, 51].

## SUPPLEMENTARY DATA

Supplementary data are available at [ndt.oup.com](http://ndt.oup.com).

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## AUTHORS' CONTRIBUTIONS

Y.O. was responsible for the research idea and study design. K.K.-Z. was responsible for data acquisition. M.W., Y.O., E.S., C.M.R., J.C., C.H., C.P.K. and K.K.-Z. were responsible for data analysis/interpretation. M.W. and Y.O. were responsible for statistical analysis. C.P.K. and K.K.-Z. provided supervision or mentorship. Each author contributed important intellectual content during manuscript drafting or revision and accepts accountability for the overall work by ensuring that questions pertaining to the accuracy or integrity of any portion of the work are appropriately investigated and resolved.

## CONFLICT OF INTEREST STATEMENT

K.K.-Z. has received honoraria from Abbott, AbbVie, Alexion, Amgen, AstraZeneca, AVEO, Chugai, DaVita, Fresenius, Genentech, Haymarket Media, Hospira, Kabi, Keryx, Novartis, Pfizer, Relypsa, Resverlogix, Sandoz, Sanofi-Aventis, Shire, Vifor, UpToDate and ZS Pharma. Y.O. has received honoraria from Ono and Chugai.

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